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Mortality of Monarch Butterflies (*Danaus plexippus*) at Two Highway Crossing "Hotspots" During Autumn Migration in Northeast Mexico

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The contribution to annual mortality of migrating monarch butterflies (*Danaus plexippus*) due to collisions with vehicles is poorly understood but likely significant. Recent estimates based on a study in Texas suggests that mortality during autumn migration may be of the order of 2 million per year or about 3% of the population. However, MaxEnt models used in that study are not well suited to quantifying mortality at hotspots where monarchs are concentrated by topography such as canyons when crossing highways. Potentially catastrophic mortality could occur at such sites if timing of migration and weather conditions conspire to force a large proportion of the migrating population across highways at low altitude. We investigated monarch mortality 15 October to 11 November, 2018 at two highway crossings in northeastern Mexico known for their frequent and extensive collisions (La Muralla and Santa Catarina). During a 15–19 day period of migration, we collected dead and injured monarchs along a series of 500 m roadside transects. We estimated a minimum total mortality during fall migration at just these sites of about 196,560 individuals. Monarchs exhibited a diurnal pattern of passage at Santa Catarina of peaks in late morning and late afternoon. Average vehicle speeds exceeded posted 60 km/h limits designed to protect monarchs, ranging from 75.1 to 99.6 km/h at La Muralla and 86.6 to 106.8 km/h at Santa Catarina. We recommend finer-scale documentation of migration pathways and an inventory of significant highway crossing hotspots for monarchs during fall migration in northeast Mexico. Mitigative measures could include better enforced vehicle speeds at least during the short period of migration, deflection structures to raise the height of crossing monarchs, and/or manipulation of habitat to lower the potential for monarchs descending to roost near key crossing points.

Keywords: roadkills, mortality, vehicles, migration, mitigation

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INTRODUCTION

The eastern North American population of the monarch butterfly (*Danaus plexippus*) migrates annually from natal sites primarily in the eastern United States and southeast Canada to overwintering sites in the highlands of central Mexico. This journey represents an iconic example of long-distance insect migration and is the focus of tremendous public and scientific interest.

Currently, conservation of this population is of considerable concern due to long-term declines in the population of migratory individuals (Vidal and Rendon-Salinas, 2014; Thogmartin et al., 2017). Causes of the decline are not well understood, but the disappearance of milkweed host plants on the breeding range, loss or reduction in quality of overwintering sites in Mexico and long-term factors associated with increased use of pesticides and global climate change are all areas of current research (Flockhart et al., 2017; Pleasants et al., 2017; Agrawal and Inamine, 2018; Tracy et al., 2019). Less attention has been placed on factors operating during the migratory phase which can be up to 4,000 km for some individuals. During migration, monarchs must fuel their journey through nectaring at stopover sites *en route*. They must also secure safe roost sites each evening and ultimately capitalize on suitable winds to aid their migration. Collisions with vehicles has been raised as a potentially important mortality factor for migrating Lepidoptera including monarchs (McKenna et al., 2001; Rao and Girish, 2007; Her, 2008; Skórda et al., 2013; Bennett, 2017; Tracy et al., 2019). However, this topic has been largely ignored apart from anecdotal accounts of roadkill hotspots, especially in south Texas and northeastern Mexico (Correo Real, 2015; Journey North, 2017). Recently, Kantola et al. (2019) used a MaxEnt niche model to estimate monarch mortality due to roadkills during Autumn migration through the Central Funnel, or the constricted flyway from Oklahoma to the Mexican overwinter sites. Their model was based on field data collected in Texas 2016–2017 and extrapolated to highways that occur in the rest of the region. These authors estimated that an average of 2.1 million monarchs are killed annually in the funnel representing about 3% of the overwintering monarch population. Their model provided a useful means of estimating mortality but lacked data from Mexico. Furthermore, the model was less suited to dealing with modeling mortality at acute hotspots where a large percentage of the autumn migration may be funneled by local topography across major highways as occurs in northeast Mexico (Correo Real, 2015).

The general autumn route taken by monarchs from their natal sites to overwintering sites in Mexico are generally known, but specific details on local routes are still lacking. From nectaring and staging sites in Texas, monarchs migrate in large numbers through and along the Sierra Madre Oriental mountains in Coahuila and Nuevo Leon of northeast México and along the eastern cordillera before crossing westward to their high altitude wintering sites in Michoacáan and México states (**Figure 1**). This route in Mexico is characterized by acute concentrations whereby a large percentage of the total migratory population funnels through canyons, river valleys, and other topographical features.

It is at those concentrations or bottlenecks where the population is most susceptible to local conditions. During our own research in northeast Mexico in the vicinity of Monterrey, we became aware of two highway crossings where it was well known among local people that considerable monarch mortality occurs annually during the autumn migration. The non-governmental organization, Protección de la Fauna Mexicana (PROFAUNA) as part of their Correo Real initiative, have reported significant roadkill at six highways: Highway MEX 054, Saltillo-Concha del Oro, Coahuila; Highway MEX 030, Cuatro Ciénegas, Coahuila; Highway MEX 057, La Muralla, Coahuila; Highway MEX 057, Jaguey de Ferniza, Saltillo, Coahuila; Highway MEX 040, Saltillo-Monterrey; toll Highway MEX 040-D Saltillo-Monterrey, Santa Catarina, Nuevo Leon. One observer counted 115 dead monarch butterflies in the ditch of the toll Highway MEX 040-D in Santa Catarina, Nuevo Leon (Correo Real, 2015) and we believe this to be the first quantitative report of roadkilled monarchs in Mexico. These anecdotal accounts prompted us to attempt the first quantitative estimates of monarch mortality due to vehicle collisions at key points where migratory routes intercept major highways in northeast Mexico.

Our objectives were to focus on two sites well known for their highway collisions with monarchs and to quantify the mortality rates at these sites during the complete passage period. In addition to counting and collecting killed monarchs, we also monitored overall diurnal patterns of movement through these sites. Here, we wished to identify if there were key periods during the day when monarchs were more susceptible to collisions as such information would inform potential mitigation measures. Height of migrating monarchs was also estimated in order to evaluate the percentage of migrants more at risk due to collisions. Our own observations indicated that monarchs flying under 6 m were most at risk with collisions or disturbance from the taller transport trucks so we quantified numbers migrating above (to 20 m) and below that threshold. We additionally aimed to quantify traffic speed at these crossings using hand-held radar and to compare average vehicle speed and type with legislated speed limits. Local authorities have posted signs to alert motorists to crossing butterflies and have specified 60 kilometers/h limits in these regions to reduce monarch mortality but it is not clear if motorists pay any attention to these measures.

Our investigation also complements the recent MaxEnt based model of Kantola et al. (2019) because that study was based entirely on a sample ($n = 546$) of roadkilled monarchs in Texas and while these authors considered hotspots separately from chronic background mortality rates, conditions leading to hotspot mortality areas can be diverse and highly dependent on local conditions which are hard to model. In addition, hotspots identified in Texas by Kantola et al. (2019) were more diffuse occurring over tens of km whereas the hotspots we identified and studied were much more narrow, corresponding to a funneling of the migration primarily over < 5 km. While mortality at these sites is expected to differ considerably among years, depending on local weather conditions and the nature of the migration, they also represent sites where potentially catastrophic mortality can occur.

MATERIALS AND METHODS

Monarch Mortality

Field sites were chosen based on our consultation with local people and observers from Correo Real. During the autumn of 2018, we focused on two highways along the Sierra Madre Oriental in the state of Coahuila and Nuevo Leon where monarch butterflies funnel during southward migration (**Figure 1**). One site was on Highway MEX 057, Saltillo-Monclova (landmark

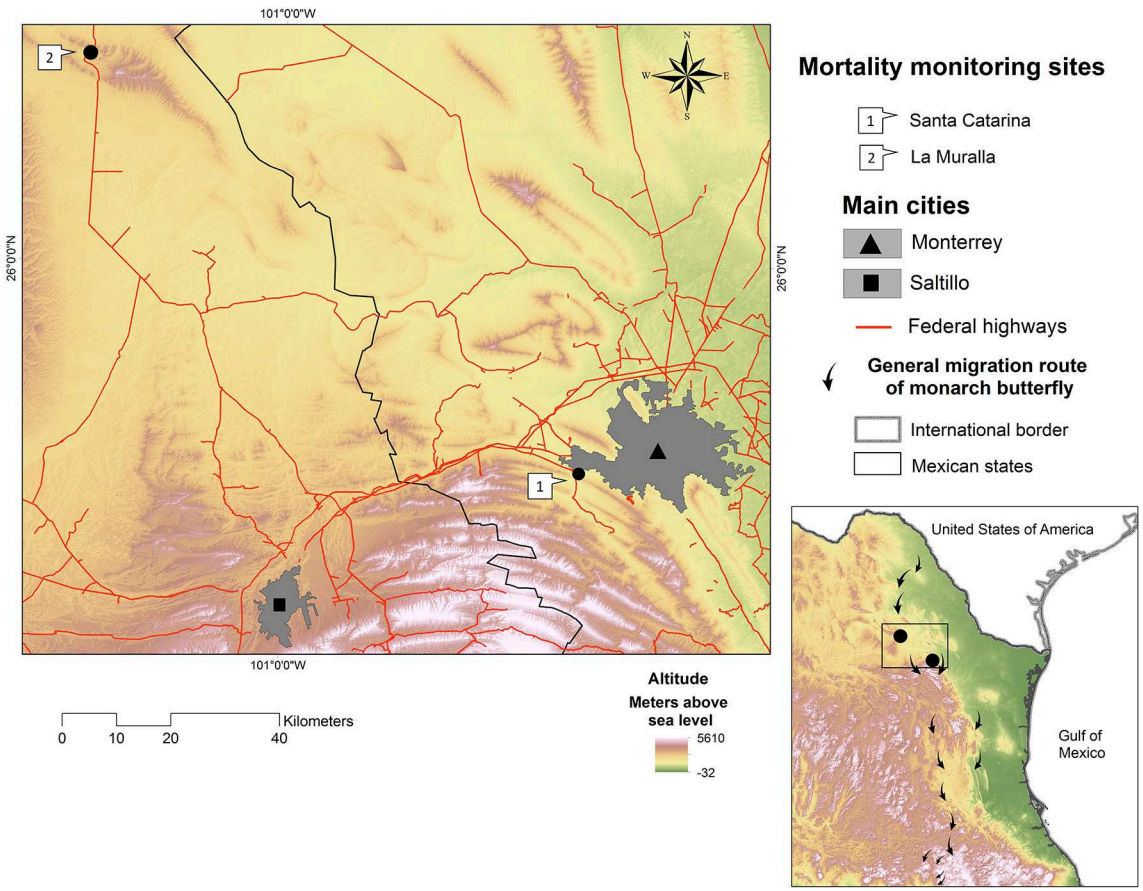

FIGURE 1 | Location of the study area used during the autumn migration of 2018 with the two highway crossings indicated. Arrows indicate approximate autumn migration route through northeastern Mexico.

km 128, 26° 36′ 72.15″N, 101° 35′ 53.17″ W) in La Muralla, Coahuila. Along a 10 km extent, the highway follows the base of the mountains with both narrow and wide areas. Two deep major canyons cross the road where high mortality occurs. We focused on a 5 km section of the highway centered on the main canyon crossing (**Figure S1**). The second site was on toll-Highway MEX 40-D, Saltillo-Monterrey (land mark km 58, 25° 39′ 18.54″N, 100° 27″ 12.24″W) in Santa Catarina, Nuevo León. Mountain ridges at this site concentrate monarchs during migration and force a cross-highway passage (**Figure S2**). This toll highway is parallel to a much busier free road (Mex-040) but we were able to sample only on the toll highway. At both study sites, the highways dissect natural habitat of the region with little to no human habitation. The La Muralla site has single lane traffic in each direction and the Santa Catarina highway had two lanes in each direction with a parallel single lane free highway (Mex-040) adjacent.

Transects (500 m) were established along sections of highways in order to quantify monarch mortality. Transects were placed to sample sections of highway and also before and after bridges crossing canyons as these were the most likely sites for monarch passage as well as open areas (e.g., Morris et al., 2015). However, transects were spaced as uniformly as possible in order to capture the total crossing width of the migration at each site. These transects included the shoulder pavement and the ditch, a width which varied depending on the highway and region of the highway sampled. Very few dead or injured monarchs remained on the actual highway and were typically blown to the side. In addition, the main highways were too dangerous to attempt retrieval from those locations. Surveys were performed on one side of the highways and all dead and dying monarchs were collected and placed in plastic bags (**Figure S3**) and archived at the Wildlife Laboratory at the University of Nuevo León. All transects were conducted on consecutive days to ensure each sample represented mortality over a 24 h period. In La Muralla, we established six 500 m transects (i.e., 3,000 m) of 2.9 m width over a total distance of 6 km. In Santa Catarina, we had five transects of 500 m length and 3.4 m width over 14 km. Variable widths of transects reflected local conditions of ditch width and pavement verge. We consider these widths to accurately reflect the sampling regions of the two sites (i.e., where dead monarchs accumulated).

Observations of Migrating Monarchs

Daily counts of flying monarchs were conducted at chosen transect points. Observers were stationed at different crossing

points and monarchs counted for two 20 min periods each hour (i.e., a total of 40 min/h). We separated flying monarchs into two height categories, 0–6 and 6–20 m. The 6 m threshold corresponded to our estimate of the influence of the taller transport truck vehicles and the 20 m upper limit was based on the fact that this range proved to be manageable for observers. In La Muralla, counts of flying monarchs were conducted at two locations (2 observers each concentrating on different height categories) for 12 days between 09:00 h until 16:30 h (26.355 N, 101.355 W; 26.367 N, 101.355 W) and at Santa Catarina by one observer (recording both height categories) at one location for 16 days between 10:30 and 16:30 h (25.653 N, 100.453 W).

Vehicles

We estimated vehicle speed across random assays with a hand-held radar system (SPEEDSTER III- Bushnell), delineated according to the categories passenger vehicle (including SUVs), light truck, and heavy (transport) truck. These categories were used because we realized that the threat to flying monarchs will depend on a combination of the speed and size of the vehicle but we had no *a priori* expectation of how these factors would interact and direct monarch mortality associated with vehicle type could not be recorded. We did not record which lane target vehicles were using.

RESULTS

We were able to judge the start of migration at both sites by driving the routes and looking for dead monarchs on the roads or flying. Rain prevented migration for periods of several days and this dictated largely our attendance at sites during the migration period. At the La Muralla site, during 84 transects over 15 days (15 October to 7 November 2018), we collected a total of 601 roadkilled monarchs (0.14 monarchs/m/d; **Figure 2A**). Unfortunately, we were unable to sample the complete monarch migration period at La Muralla which extended from 22 October through 14 November. At Santa Catarina, during 95 transects over 19 days (24 October to 11 November) we collected 11,280 monarchs (0.24 monarchs/m/d; **Figure 2B**). Again, we were forced to terminate our work before the end of the migration period which lasted until 24 November. These counts represented about half of the actual mortality on each transect because only one side of the highway was sampled and so should be doubled (La Muralla: 0.28 monarchs/m/d; Santa Catarina 0.48 monarchs/m/d). This allowed us to estimate the total mortality over the actual crossing distances and duration of our study assuming our transects were representative of each crossing (La Muralla: 0.28*6000*14 = 23,520; Santa Catarina: 0.48*14000*19 = 127,680). Because we terminated our fieldwork before the end of the migration period we consulted with Correo Real, who continued to conduct migration monitoring at both locations. Based on those consultations, we feel that each estimate of the actual monarch mortality could be increased by 30% at both sites. That decision was based on the fact that at least one third of the total migration at each location was not documented but the intensity of the migration was also diminishing. So, we suggest a reasonably conservative estimate of total mortality at La Muralla to have been 30,576 and at Santa Catarina 165,984. Our Santa Catarina estimate was also considered to remain an underestimate because we were unable to sample at the parallel and busier free highway (Mex-040).

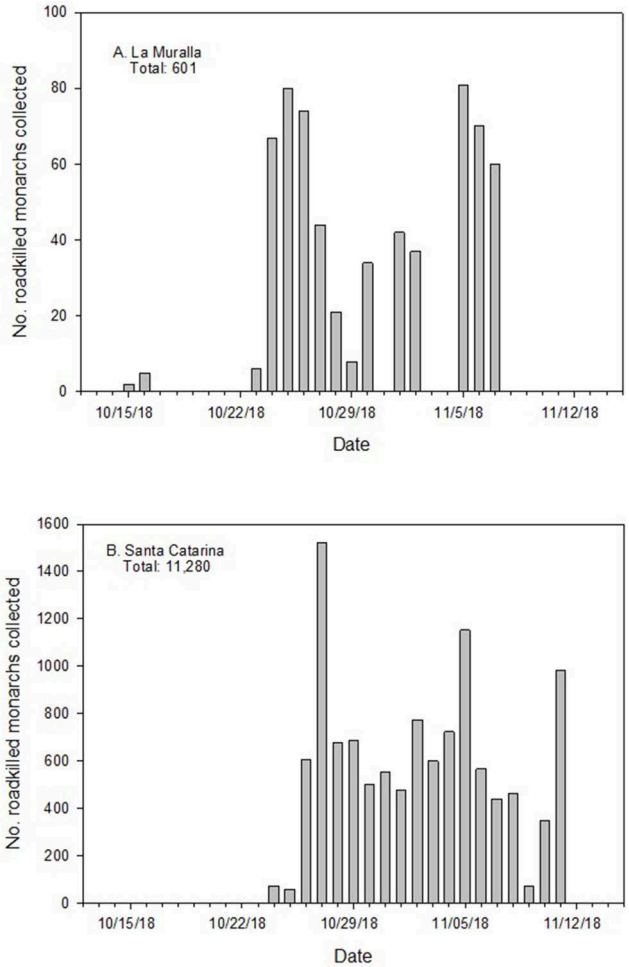

FIGURE 2 | Pattern of roadkilled monarchs collected during daily transects at **(A)** La Muralla (15 October−7 November) and **(B)** Santa Catarina (24 October−11 November). Days showing no monarchs collected within the sampling periods indicated were due to a halt in the migration.

At La Muralla, peak movements of monarchs tended to be in the morning and evening (**Figure 3A**). At the Santa Catarina crossing, we observed a more distinct bimodal pattern of diurnal migration (**Figure 3B**) with peak movements during 1,100–1,200 h and from 1,430 to 1,600 h. During 16 days of regular counts at Santa Catarina, we recorded 203,240 flying butterflies and, of these, 41.4% were crossing the highway below 6 m. At La Muralla, we recorded 25,060 crossing monarchs and of these, 24.8% crossed below 6 m.

The average speed of cars, light and heavy (transport) trucks all exceeded local speed limits (**Table 1**). Daily traffic average volumes (including both directions) were available from Secretaría de Comunicaciones y Transportes for Santa

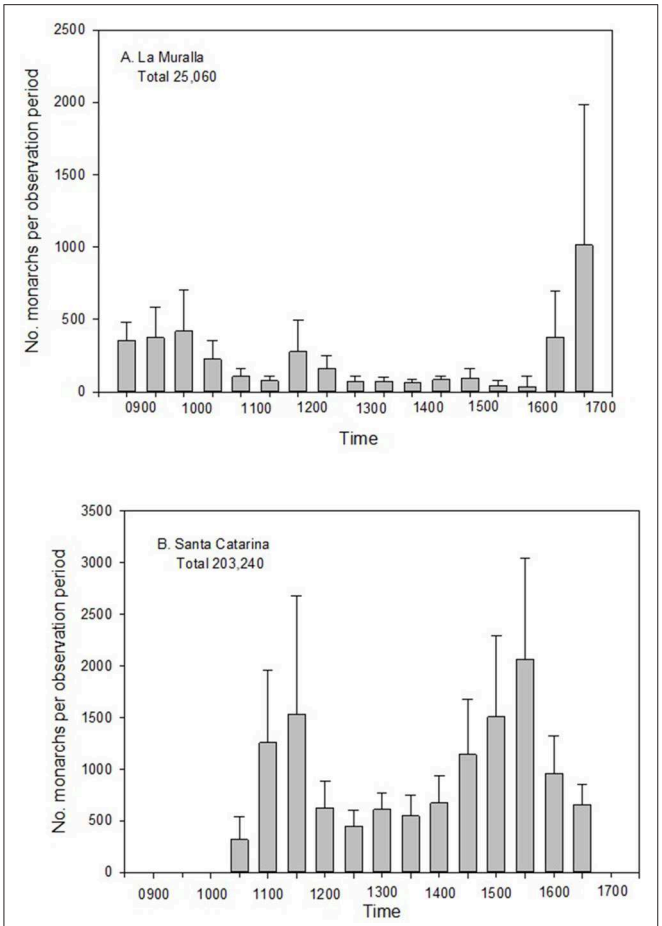

FIGURE 3 | Pattern of diurnal movements of migrating monarchs through **(A)** La Muralla (15 October−7 November) and **(B)** Santa Catarina (24 October−11 November).

Catarina in 2018[1] and these were 14,330 vehicles for La Muralla and 8,862 vehicles for the Santa Catarina toll highway (Mex-040D) and 41,377 (both ways) for the parallel free highway (Mex-040; SCT 2019).

DISCUSSION

We provide for the first time quantitative estimates for monarch mortality during autumn migration at two highway crossings in northeast Mexico. We estimated that a minimum of 196,560 monarchs were killed by collisions with vehicles during their short and concentrated crossings at these two sites in 2018. We consider this estimate to be conservative, in part, because we did not sample at the busier parallel highway (Mex-040) at Santa Catarina. We stress that these estimates are for only two sites but are significant because they represent points where a large proportion of the entire eastern population of North American monarchs concentrate *en route* to wintering grounds. Lower but more chronic mortality rates are expected in regions where monarchs are much less concentrated (Kantola et al., 2019). However, there are numerous highways in Mexico which involve monarch crossings and mortality rates there are yet to be estimated. We have provided descriptions of the six sites in northeast Mexico provided by Correo Real and these would be a useful starting point.

Monarchs crossing the La Muralla site were primarily in transit and we observed little structure in their diurnal movements. At Santa Catarina, however, monarchs appeared to look for roost sites in the vicinity of the highway at the end of the day and this typically brought them to lower altitudes where they were more vulnerable to collisions. This observation is important because it suggests that mitigative measures may be appropriate in terms of roadside habitat manipulations (Skórda et al., 2013) in the vicinity of the Santa Catarina hotspot.

We argue that potentially catastrophic mortality could occur at these sites where canyons concentrate a vast proportion of the migratory population. Should weather conditions force monarchs to pass below 6 m over these roadways and traffic passes at high speed and at high volumes, then substantially higher mortality rates than we recorded are expected. We observed that rain halted migration and that local winds clearly can influence vulnerability to road crossing mortality. Future work at hotspots should measure these conditions. While mitigative measures to prevent butterfly mortality have been largely unexplored, we contend that traffic speed is an issue and one which can presumably be enforced at least for the short period of monarch autumn migration. Our observers noted many butterflies injured simply due to wind vortices (vs. actual collisions) caused by high speed vehicles with effects apparent to 6 m, especially for large transport trucks. Presumably, the concentrated nature of these crossings temporally and spatially lend themselves to tailored actions for short periods. This could involve increased use of temporary but more effective speed restrictions through radar traps or simple police presence. Apparently, signage warning motorists to slow down for butterfly crossings (**Figure 4**; https://www.milenio.com/cultura/caminos-pasa-monarca-limite-60-km) is ineffective.

Alternatively, more ambitious solutions could involve structures that would deflect monarchs over these crossings. For example, in Taiwan, the double-banded crow butterfly (*Euploea sylvester*) migration crosses major highways and mitigative measures taken to protect this species have included the construction of over a kilometer of four-meter high protective netting. Those measures have apparently reduced the mortality from 20–30 per thousand in 2007 to 4.7 per thousand in 2009 (Taiwan Environment Protection Administration, 2010). Certainly, close monitoring of the autumn migration of monarchs in the areas we studied could provide predictions of timing of movements when direct and effective action could be applied for relatively short periods (in the case of traffic speed restrictions) or more permanently (in the case of erected netting).

We consider our work preliminary and not yet at a level where absolute mortality estimates are possible for the fall migration. Future studies could provide an estimate of the proportion of

[1]Secretaria de Comunicaciones y Transportes http://www.sct.gob.mx/carreteras/direccion-general-de-servicios-tecnicos/datos-viales/2019/

TABLE 1 | Summary of vehicle speeds (km/h) recorded at the two study locations in northeast Mexico October-November 2018.

Site	Passenger vehicle				Light truck				Transport truck			
	n	Mean	SD	Range	*n*	Mean	SD	Range	*n*	Mean	SD	Range
La Muralla	305	99.6	16.9	57–161	183	94.2	16.8	51–153	167	75.1	17.0	10–130
Santa Catarina	210	106.8	19.6	42–153	96	108.9	17.6	40–168	11	86.6	20.7	43–110

Posted speed limits were 60 km/h at both sites.

FIGURE 4 | Sign indicating the speed limit 60 km/h in the area of monarch highway crossing. Highway 57 at the La Muralla study site, Coahuila. Photo by Omar Franco Reyes.

monarchs killed to those flying over but this would require several observers recording continuously throughout the day. The potential for high altitude flight (beyond observer range for counting) also suggests that radar may assist in estimating monarch movements at such concentrations (Ovaskainena et al., 2008). So, it is currently unknown if highway mortality in Mexico and elsewhere is a significant and additive mortality factor and could be contributing to population declines. On the other hand, it is clear that traffic volumes are increasing and monarchs are facing more and more sites where collisions occur and are increasing. Monterrey is the third largest city in Mexico (4.8 million) and continues to grow at about 1.2% per year (https://populationstat.com/mexico/monterrey). This city intercepts a major portion of the eastern continental monarch migration. Future studies should attempt to refine mortality estimates annually at key sites in Mexico where monarch mortality has been identified. We need to know more about specific routes taken by monarchs and identify where these sites intercept significant highway crossings. Mitigative measures need to be explored but we suggest that the provision of suitable and extensive roost sites away from highway crossings may be a way of inducing monarchs to travel on to these "safe" sites to roost and so avoid low altitudes around highways, at least later in the day. The same principle could apply to nectar lure crops to again attract monarchs away from vulnerable highway sites. At other sites, the only feasible solution appears to be the construction of high (∼8 m) netting to deflect monarchs over the highway.

We recommend that estimates of monarch mortality due to collisions with vehicles be conducted throughout the Mexican portion of the autumn flyway. This would allow direct testing and refinement of the MaxEnt model derived by Kantola et al. (2019) for this critical component of the migratory funnel. In addition, mortality estimates need to be continued at known hotspots as done here. Mitigative measures should be developed and experiments conducted to evaluate their effectiveness. Finally, we noted that monarch mortality at hotspots is apparently absent during the spring northward migration in the region where we worked. It is not clear if monarchs take alternate return routes at that time that are "safer" in terms of highway collisions. However, the magnitude of the spring migration in northeastern Mexico will be considerably less than that in autumn due to overwinter mortality.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Only roadkilled monarchs were used in this study and so no ethical considerations or animal care permits required. All Mexican permits issues to RC-T.

AUTHOR CONTRIBUTIONS

BM and KH conceived of the project and all authors contributed to the study design. BM conducted most of the fieldwork. All authors helped to write the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2019.00273/full#supplementary-material

Supplementary Figure S1 | Highway 57 at the La Muralla study site, Coahuila. Photo by B. Xiomara Mora Alvarez.

Supplementary Figure S2 | Toll highway 40-D at the Santa Catarina study site in Nuevo León. Photo by Omar Franco Reyes.

Supplementary Figure S3 | Bags of dead monarchs collected on one transect day from the Toll Highway 40-D in Santa Catarina, Nuevo León. Photo taken by Rogelio Carrera Treviño.

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