Evaluation of Different Methods to Identify Sites that Require Safety Investigations

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RESEARCH & DEVELOPMENT

Evaluation of Different Methods to Identify Sites That Require Safety Investigations

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One of the first steps in effectively managing a road network is to identify sites that require safety investigations. It is important that this process of identifying the 'sites with promise' be efficient because scarce resources may be wasted on sites that are incorrectly identified as unsafe and sites that are truly unsafe may not be flagged in this process. The original objectives of this research were to compare the performance of different screening methods and determine if particular method(s) are more optimal for identifying locations susceptible to cost-effective safety improvement. The investigation of the sites was scheduled to be done by NCDOT but could not be undertaken due to budget constraints. Hence, as an outcome of this project, the project team developed safety performance functions (SPFs) and developed a network screening algorithm that can be implemented to identify sites using methods discussed in the HSM. This algorithm was provided as a SAS program for NCDOT to use.</td></tr>
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EXECUTIVE SUMMARY

One of the first steps in effectively managing a road network is to identify sites that require safety investigations. It is important that this process of identifying the 'sites with promise' be efficient because scarce resources may be wasted on sites that are incorrectly identified as unsafe and sites that are truly unsafe may not be flagged in this process. Conventional methods that make use of just accident counts or accident rates (per unit of exposure) are now known to have problems because they do not effectively account for the potential bias due to regression-to-the-mean phenomenon in which sites with a randomly high account could be incorrectly identified as being hazardous and vice versa. Another problem with conventional methods that makes use of crash rates is the implicit assumption that crash frequency and traffic volume are linearly related, i.e., that a 20% increase in volume will result in a 20% increase in crashes; many recent studies have shown that the relationship between crashes and volume is non-linear, and this relationship depends on the type of facility.

The original objectives of this research were to compare the performance of different screening methods and determine if particular method(s) are more optimal for identifying locations susceptible to cost-effective safety improvement. The intent was to include multiple methods including the method currently being used by NCDOT as part of the HSIP program, and methods discussed in the HSM. The intent was to identify potential sites using different methods and investigate the sites to determine appropriate countermeasures. This task was scheduled to be undertaken by NCDOT due to their experience in conducting these types of investigations. However, NCDOT was unable to conduct these investigations due to budget constraints. Hence, as an outcome of this project, the project team developed safety performance functions (SPFs) and developed a network screening algorithm that can be implemented to identify sites using methods discussed in the HSM. This algorithm was provided as a SAS program for NCDOT to use.

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1. INTRODUCTION

One of the first steps in effectively managing a road network is to identify sites that require safety investigations. It is important that this process of identifying the 'sites with promise' be efficient because scarce resources may be wasted on sites that are incorrectly identified as unsafe and sites that are truly unsafe may not be flagged in this process. Conventional methods that make use of just accident counts or accident rates (per unit of exposure) are now known to have problems because they do not effectively account for the potential bias due to regression-to-the-mean phenomenon in which sites with a randomly high account could be incorrectly identified as being hazardous and vice versa. Another problem with conventional methods that makes use of crash rates is the implicit assumption that crash frequency and traffic volume are linearly related, i.e., that a 20% increase in volume will result in a 20% increase in crashes; many recent studies have shown that the relationship between crashes and volume is non-linear, and this relationship depends on the type of facility.

As part of the Highway Safety Manual (HSM) (HSM, 2010), methods based on the empirical Bayes (EB) procedure have been proposed to identify locations with promise. In theory, the EB methods are considered superior because they have been shown to be more effective in controlling for the possible bias due to regression to the mean (RTM) and also explicitly account for the fact that the relationship between crash frequency and traffic is not necessarily linear. However, very little work has been done to compare the performance of the EB methods with other methods. The intent of this proposed project is to compare the performance of different methods and find out if a particular method is more optimal for identifying locations susceptible to cost-effective safety improvement.

OVERVIEW OF METHODS TO IDENTIFY SITES WITH PROMISE

Methods used by NCDOT as part of the Highway Safety Improvement Program (HSIP)

In order to identify sites as part of the HSIP program, NCDOT has developed a system of safety warrants to identify locations that are possibly deficient[1]. Detailed crash anlaysis are performed at the locations that meet the warrant criteria and have more severe and correctable crash patterns. The regional traffic engineering staff perform engineering field investigations at these locations. Based on these investigations, countermeasure are identified.

In order to identify sites as part of the 2019 HSIP program, NCDOT has developed warrants based on the non-PVA reportable crashes occurring between 2014 and 2018 (2009 through 2019 for warrants requiring 10 years of data)[2]. Warrants are intended to identify a specific crash type, pattern, or condition. Animal crashes are not included during the screening process.

For intersections and sections, there are eight warrants. There is also a warrant for bicycle and pedestrian crashes at intersections, and a warrant for bridge crashes. The intersection warrants deal with frontal impact crashes (urban and rural), increase in crashes that happened in the last year, frequency with

[1] Source: https://connect.ncdot.gov/resources/safety/Pages/NC-Highway-Safety-Program-and-Projects.aspx

[2] Source: https://connect.ncdot.gov/resources/safety/HSIP%20Library/2019%20HSIP%20Warrants.pdf

severity index, number and percentage of crashes that occur at night. For sections, the warrants deal with run off road crashes during wet conditions on freeways, run off road crashes on freeways, wet condition crashes on freeways, percentage of crashes during night on freeways, run off road crashes during wet condition in non-freeways, run off roads crashes in non-freeways, wet condition crashes on non-freeways, and non-intersection night crashes in non-freeways. The warrants are based on crash counts, crash rates (per mile for sections), and percentage of specific crash types. NCDOT also provided a document with the ranking formulas showing the calculations for weighting factors.

Methods discussed in the HSM

Chapter 4 of the HSM (HSM, 2010) discusses the advantages and disadvantages of the following methods for network screening:

- Average crash frequency
- Crash rate (based on traffic volume)
- Equivalent property damage only (EPDO) average crash frequency
- Relative severity index
- Critical rate
- Excess predicted average crash frequency using method of moments
- Level of service safety
- Excess predicted average crash frequency using safety performance functions (SPFs)
- Probability of specific crash types exceeding threshold proportion
- Excess proportion of specific crash types
- Expected average crash frequency with Empirical Bayes (EB) adjustment
- EPDO average crash frequency with EB adjustment
- Excess expected average crash frequency with EB adjustment

Some of these methods are based only on crash frequency and severity while others make use of traffic volume either by computing a crash rate or by making use of safety performance functions (SPFs). The advanced methods in the HSM use the EB approach to specifically account for possible bias due to regression to the mean (RTM). The EB approach computes the expected crash frequency at a site as the weighted average of the observed crashes and the predicted crash frequency based on a SPF. So, instead of using the observed crash frequency to rank sites, the expected crash frequency is used and by doing this it reduces the possibility of bias due to RTM. The difference between the expected crash frequency and the predicted crash frequency (from a SPF) is called as the expected excess crash frequency. When this expected excess crash frequency is greater than zero, then a site experiences more crashes than expected.

The excess proportion of specific crash types is the difference between the observed proportion of a specific crash type for a site and the threshold proportion for the reference population. In a way, the use of excess proportions is similar to NCDOT's approach for identifying sites with a correctable pattern of crashes.

Among the advanced methods, there has been some debate over whether expected crash frequency should be used or expected excess crash frequency should be used to identify sites for further review. *SafetyAnalyst* (a software tool from AASHTO for safety management) allows the user to choose expected crashes or expected excess crashes for network screening.

2. OBJECTIVES

The original objectives of this research were to compare the performance of different screening methods and determine if particular method(s) are more optimal for identifying locations susceptible to cost-effective safety improvement. The intent was to include multiple methods including the method currently being used by NCDOT as part of the HSIP program, and methods discussed in the HSM.

3. LITERATURE REVIEW

Many studies have tried to compare the performance of advanced methods that make use of the EB method with traditional methods such as crash frequency and crash rates. For example, Srinivasan et al. (2016) provides examples from five previous studies that compared the performance of different network screening approaches. Overall, these examples indicated that the advanced methods that make use of the EB method are able to account for the bias due to RTM and also account for the non-linear relationship between AADT and crashes.

One of the examples involved a network screening exercise based on five network screening methods using data for rural, two-lane, undivided roads in Colorado (Hauer et al., 2004). The objective of this study was to determine the network screening performance measure that is most likely to lead to cost-beneficial projects. The five network screening performance measures are as follows:

1. EB expected total: sites with the most expected crashes.
2. EB expected severity-weighted: sites with the most expected severity-weighted crashes.
3. EB expected excess total: sites with the most excess expected crashes.
4. EB expected excess severity-weighted: sites with the most excess expected severity weighted crashes.
5. Combination of EB expected and EB expected excess: the product of the expected crashes per mile-year (expressed in crashes per mile-year) and the excess crashes per mile-year (expressed in standard deviations).

The researchers employed a pairwise comparison, comparing two performance measures at a time to identify sites for further investigation and potential treatment. A detailed investigation was conducted for the top ranked sites to identify possible treatments. The EB expected severity weighted measure resulted in the most cost-effective projects.

Gross et al. (2016) used data on intersections from New Hampshire and ranked lists of sites based on four network screening performance measures (crash frequency, crash rate, EB expected, EB expected excess), performed a safety diagnosis on the top ranked intersections, developed potential strategies to target the underlying safety issues, and conducted an economic analysis for each intersection improvement package. The EB excess expected measure[3] and the EB expected measure produced the list of sites with the highest overall economic benefit and the highest return on investment, respectively. The crash rate measure produced the lowest overall economic benefit and the lowest return on investment.

Overall, the previous work indicates that the measures based on the EB method perform quite well compared to traditional methods. However, none of the previous studies used data from North Carolina, and the comparisons did not specifically involve the methods that are part of North Carolina's HSIP.

[3] The EB excess expected measure is also called the potential for safety improvement (PSI).

4. ORIGINAL SCOPE OF WORK

Based on the proposal that was accepted by NCDOT, the following tasks were proposed:

Task 1. Survey of States

The objective of this task was to conduct a targeted survey of selected states that have implemented more advanced network screening methods. The intent of the survey was to try to determine if the advanced methods that have been implemented are identifying locations that are more susceptible to cost-effective safety improvements. Following is a summary of notes based on interviews with selected States:

Connecticut

- Until 2014, the critical crash method was used for network screening.
- In the last few years, safety performance functions (SPFs) and the empirical Bayes (EB) method are being used. Expected excess crashes are estimated and provided for Connecticut DOT to use. Critical crash rates are also provided if Connecticut DOT decides to use them.
- Expected excess crashes are provided for different crash types and severities. Connecticut DOT decides which ones to use. For network screening, both sliding window and peak search algorithms are being used.
- SPFs are mainly for state roads and higher order non-state roads that have AADT. When traffic volume is not available, average crash frequency and method of moments are used.
- SPFs use functional classification, ownership, AADT, presence of intersections, number of lanes, and area type. SPFs for freeways also includes speed change area and one-way versus two-way designation.
- SPFs are based on 2012 to 2016 data. Currently SPFs are not calibrated while estimating the expected excess crashes, but they will be calibrated in the future.
- Starting to use the systemic method for identifying sites, but this would require additional data collection.
- LIDAR is being used to get data for the roadside. Videologs are also available.

Florida

- Earlier, Florida used hot spot analysis (based on crash rate and crash frequency) to identify sites for investigation.
- Tried to use *SafetyAnalyst* but could not make it work.
- Developed SPFs in-house for signalized intersections on the State network based on the latest 3 years of data. Signalized intersections were grouped based on context classification (based on the Complete Streets concept). SPFs are estimated for each classification grouping. The next step is to do this for roadway segments and unsignalized intersections.
- SPFs were estimated using SAS for fatal and severe injury crashes. Major road AADT and Minor road AADT were used as independent variables for the SPFs.
- Florida DOT has a system that allows them to view/visualize the “problem” intersections compared to sister intersections, i.e., intersections with similar volumes.

- Florida DOT has done some systemic analysis, e.g., to examine lighting deficiencies. They have also used systemic analysis for curve compliances and will be examining South Carolina's approach for low-cost intersection improvements.
- In 2021, Florida DOT has acquired the SPF tool (developed by Tatum Group https://tatumgrp.com/systematic-safety/) for visualization and dynamic reporting.

Illinois

Obtained limited information from Illinois DOT. Further information may be available from a webinar scheduled for April 16, 2021, and consultants working with Illinois DOT.

- Network screening done by consultants for different facility types. SPFs are estimated for each facility type, and the potential for safety improvement (PSI) (based on the EB method) is estimated for severe injury crashes (KAB).
- Based on the PSI, sites are categorized as High, Medium, and Low.
- For crash types overrepresented over a period, ILDOT is in the process of identifying systemic countermeasures.

Kansas

- Earlier, a spreadsheet tool was used for network screening. Different agencies within Kansas were asked to submit projects. Each agency used their own process but considered critical crash rate.
- Kansas DOT has been using *SafetyAnalyst* since 2017 or 2018 and hopes to continue to use it for some more time, although *SafetyAnalyst* is being discontinued. Using *SafetyAnalyst* has helped with identifying solutions including benefit cost analysis.
- Default SPFs in *SafetyAnalyst* are being used.
- Level of Service of Safety is being used with a focus on level of service III and IV, and an attempt to focus on all districts as much as possible.
- Total crashes and crash patterns are being used in the process but unclear how exactly.
- Kansas DOT is exploring the possibility of using the SPF tool (developed by Tatum Group https://tatumgrp.com/systematic-safety/).

Kentucky

- In the past, the critical rate factor method was used.
- Recently, Kentucky has started using SPFs along with EB methods. For both methods, 3 to 5 years of data are used.
- The initial focus of the EB methods is state maintained roads. Within that, SPFs have been estimated for rural two-lane roads with speed limit 50 mph or greater. The primary focus is on run off road crashes. The SPFs are based on AADT and segment length.
- Kentucky is trying to use a similar procedure for intersections. For intersection level analysis, county level AADT estimates are used if more reliable counts are not available.
- Kentucky has a model for estimating AADT for segments, but this procedure has not been used in practice.
- Developing SPFs for interstates with a focus on median cross-over crashes.

- Eric Green from Kentucky DOT is developing a tool (through funding from FHWA) that can be used by practitioners to estimate SPFs. This is being done to facilitate State DOT personnel who are not comfortable with writing code and statistical analysis, to be able to estimate SPFs.

Massachusetts

- A dashboard application has been developed for network screening.
- SPFs for Massachusetts were developed by consultants. Expected excess is used for screening.
- The top 5% of sites identified by network screening can be highlighted in red.
- The application provides statistics for each segment.
- Test of proportions will be available in Summer 2021.
- The dashboard application was developed using federal funds, and is available to the public through the following link: https://apps.impact.dot.state.ma.us/cdp/home

Pennsylvania

This summary is based on conversations with PennDOT and consultants that worked with PennDOT.

- Earlier, PennDOT used crash rates, critical crash rates, and crash counts, for network screening. Legislative action will be needed to remove the use of crash rates. So, crash rates still need to be produced even if they are not being used the same way.
- Current network screening approach is based on SPFs and the EB method. SPFs have been estimated for different facility types.
- PennState developed the SPFs. District specific SPFs were also estimated. The input to the SPFs is a mixture of automated PennDOT sources and manual observations. Generally, these SPFs are multi-variable SPFs that include information apart from AADT. For freeways, the base SPFs from the HSM are used, but these may be modified later.
- Based on the expected excess crashes (weighted by severity), county wide thresholds (based on data from the most recent 5 years) are established. For sites that have been selected based on this threshold, more detailed data are collected, and district specific SPFs are used for further screening.
- The results of the network screening can be seen on a map. The color in the map for individual sites is based on excess crash frequency.
- The monetary value of each severity level is based on a recent FHWA report.

South Dakota

- Earlier (more than 7 years ago), network screening was based on a blackspot analysis.
- South Dakota DOT has built a safety module based on the HSM mainly for rural 2 lane and rural intersections. It is only for the roads in the State system. Detailed data on the HSM mandated variables are available for the State system. Some data that are not available may be assigned based on functional class. State roadway network is about 8,000 lane-miles.
- Based on the information from the safety module, it is possible to obtain predicted crashes and compare with observed crashes. This information is then used to apply level of service of safety after calibration.
- After the sites are identified, a crash diagram is used for further investigation.

- South Dakota DOT has not done any comparison of the prior blackspot analysis with the HSM approach.
- South Dakota DOT is looking into different tools such as Numetric (https://www.numetric.com/), SPF tool (developed by Tatum Group https://tatumgrp.com/systematic-safety/), and the tool developed by DiExSys (https://roadsafetyanalytics.com/).

Wyoming

The project team had a brief conversation with Wyoming DOT about their procedures for network screening. Wyoming DOT provided a brief write up that discussed their use of procedures from the 1st edition of the HSM as part of the safety management process. This document outlines the crash prediction models from Part C of the HSM including the base model and adjustment factors, and the use of EB methods. Further information about the application of these for network screening is not available from the document.

Task 2. Identify methods and site types for evaluation

NCDOT identified rural two-lane roads as a primary focus for this effort. When this project was envisioned, NCDOT did not have a complete intersection inventory with major and minor road AADT. So, the focus of this effort was on segments. Regarding the methods for evaluation, the method currently used by NCDOT as part of their HSIP program was included as one of the methods because it was considered as a 'baseline' for comparison with other methods. In addition, it was decided that the evaluation would also include the advanced methods discussed in the HSM including the EB expected number of crashes and EB excess expected number of crashes (also called the PSI method).

Task 3. Apply the methods to identify sites for safety investigation

To implement the EB methods, the first step was to estimate safety performance functions (SPFs). The project team used a log-linear functional form for estimating the SPFs. With the log-linear form, the predicted number of crashes are related to the site characteristics in an exponential form as follows:

$$y = \exp\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots \ldots \beta_n X_n\right)$$

In this equation, X's are the site characteristics including AADT and segment length, β's are the coefficients that are estimated as part of the SPF, and *y* is the predicted number of crashes for a particular segment. SPFs were estimated through negative binomial regression. This process also provided an overdispersion parameter (k) for each SPF. k does not affect the estimates of predicted values from the SPFs, but do affect the empirical Bayes estimates that are derived as a weighted average of the predicted values from the SPF, and the observed number of crashes. The weights for the predicted number of crashes and the observed number of crashes are a function of k.

For every piece of a segment in the roadway, the EB expected number of crashes is calculated as follows:

$$EB_{exp} = wP + (1 - w)N$$

In this equation, P is the predicted number of crashes from the SPF, EB_{exp} is the expected number of crashes and N is the observed number of crashes. "w" is the weight that is derived based on k as follows:

$$w = \frac{1}{1 + kP}$$

The excess expected EB (also called as the PSI) = $EB_{exp} - P$

SPFs were estimated for 8 crash type and severity combinations: K (fatal crashes), KA crashes, KAB crashes, KABC crashes, run-off-road crashes, night crashes, wet pavement crashes, and total crashes. As an example, the SPF for run-off-road crashes is shown in Table 1. The Table shows the variables that were included along the coefficients, the standard errors, and the p-values. It also shows the overdispersion parameter that is needed to estimate the EB parameters.

While investigating the goodness-of-fit of the SPFs, we developed cumulative residual (CURE) plots. This plot shows the cumulative residuals versus selected variables (e.g., predicted values, AADT) in the horizontal axis. The CURE plot also generates boundaries that are a function of the standard deviation of the cumulative residuals. For a well fitting model, it is expected that most of the cumulative residuals would be within the boundaries. For most of the SPFs estimated with the North Carolina data, a significant portion of the cumulative residuals were outside the boundaries indicating that the models did not fit the data very well. It is possible that not having information on some critical variables such as horizontal curvature that are associated with crashes on rural two-lane roads is one possible factor. However, this issue needs to be investigated further by NCDOT.

To implement the measures that were derived based on the method, the authors developed a sliding window program where a window of a certain length that slides over a route. As a default, the sliding window program uses a window length of 0.3 miles that slides 0.1 mile in each step. The program can be easily modified to have a different window length, e.g., the window length can be 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 1.0, or 1.5 miles. Similarly, the sliding length can be 0.05, 0.1, 0.15, 0.3, or 0.5 miles. The input to the program includes the predicted value from an SPF. The authors deliberated on whether this program should have included routines to estimate the SPFs. However, it was felt that an appropriate SPF may be of a different functional form to the one estimated by the authors. So, in order to not limit the use of this program to SPFs of a certain form, the authors felt that it woud be appropriate to ask the users to input the predicted values from their own SPFs. In addition to providing the predictions from an SPF, the roadway file needs to be linked to the crash file so that the observed number of crashes can be determined for different portions of a route (observed number of crashes are needed to estimate the EB parameters).

Since SPFs need AADT, there are portions of the roadway inventory that cannot be included in the screening methods based on the EB method. The SAS program is provided to NCDOT along with this report. Also provided is a SAS data file that can be used as an input to run this program. The authors will be happy to discuss how this program can be used by NCDOT for their network screening purposes.

Table 1: Estimated SPF for run-off-road crashes

Parameter	Description	Estimate	Std. Error	Pr > ChiSq
Intercept		-6.283	0.107	<.0001
Natural_Log(AADT)		0.775	0.011	<.0001
AADT/1,000		-0.084	0.004	<.0001
Terrain Type	Mountainous	**Baseline**		
Terrain Type	Level	-0.232	0.019	<.0001
Terrain Type	Rolling	-0.188	0.018	<.0001
Speed Limit	30 mph-35 mph	**Baseline**		
Speed Limit	40 mph-50 mph	0.339	0.022	<.0001
Speed Limit	55 mph-70 mph	0.301	0.021	<.0001
Functional Class	Local	**Baseline**		
Functional Class	Major Collector	0.180	0.020	<.0001
Functional Class	Minor Arterial	0.205	0.028	<.0001
Functional Class	Minor Collector	0.184	0.016	<.0001
Functional Class	Principal Arterial	0.255	0.038	<.0001
Route Class	4	**Baseline**		
Route Class	2	-0.311	0.025	<.0001
Route Class	3	-0.152	0.018	<.0001
Route Class	7	-22.89	3665.225	0.995
Dispersion		0.516	0.010	

Task 4. Conduct detailed safety investigation of the sites

The goal of this task was to use the results of Task 3 to first determine the top ranked sites in each method and then conduct a detailed safety investigation of these sites. When the proposal was submitted, it was expected that the investigation of these sites would be done by trained NCDOT staff who have experience in doing such investigations. It was recognized that this task may involve the detailed review of individual crash reports followed by a safety audit of individual sites as part of a field investigation.

When the proposal was written, a 6 month time window has been allocated for the detailed investigation of these sites with the understanding that this time window may need to be adjusted depending on the resources that are available to NCDOT at that time.

The authors were able to determine the top ranked sites based on the EB expected and the PSI methods. However, unlike the methods based on the HSIP that NCDOT was using, the window lengths for the EB expected and the PSI methods were fixed, with the understanding that the screening could be repeated with different window lengths.

NCDOT indicated that they did not have the resources to conduct a detailed investigation of the sites that were identified from the EB methods. The sites identified from the HSIP method were likely investigated and possibly treated using selected countermeasures.

Task 5. Identify possible countermeasures

Using the information collected during the safety investigation, the goal of this task was to identify possible countermeasures, the expected effectiveness of these countermeasures (based on NCDOT approved crash reduction factors), and the cost of these countermeasures. This task was also expected to be led by NCDOT staff due to their experience. However, since the sites identified based on the EB method were not investigated in Task 4, Task 5 could not be performed on these sites.

Task 6. Determine the best methods

Based on the results of Task 5, this task will determine if a particular screening method is more optimal for identifying locations susceptible to cost-effective safety improvement. This task could not be performed since Tasks 4 and 5 were not done for the sites identified based on the EB methods.

Since the methods based on the HSIP and the EB methods could not be compared because resources were not available to investigate the sites selected by the EB methods, the authors and NCDOT discussed the possibility of comparing the different methods using other approaches. For example, Srinivasan et al., (2016) discusses different ways of comparing network screening methods. One approach outlined in Srinivasan et al., (2016) involves identifying which screening method leads to sites that would have more crashes in the future if they are not treated. However this approach was considered unreliable because many of the sites identified by the HSIP method were likely treated because they would have been investigated.

For these reasons, the methods based on the EB method could not compared with the methods based on the HSIP. The authors hope that NCDOT can use the SAS program that was developed by the authors for screening the network using EB methods.

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