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Electrical Characteristics & Functions

of

Inductive Loops

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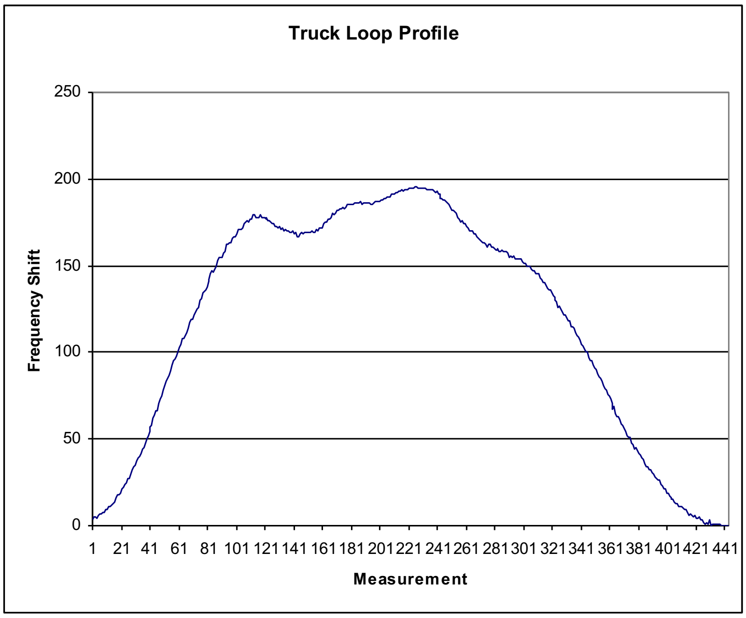
Inductive Loops

Actuation – a simplified description

The 'Loop based vehicle detector' uses inductive loop sensors (a coil of wire) located in the roadway to detect vehicles. The in-pavement loop is an extension of an electronic circuit which detects changes in electrical characteristics of the loop when a metal mass transgresses the loop. Each loop is scanned individually for a change in inductance resulting from the interaction between the loops electromagnetic field and the 'eddystone' current fields in the metal mass of a vehicle transgressing the in-pavement loop field. A change of frequency resulting from a change of inductance signifies a mass of metal i.e. a vehicle is passing within its field. If the change is above a threshold determined from the sensitivity setting for the loop, an actuation is signalled.

The figure below displays the frequency shift when a truck is travelling over a loop:



Therefore the characteristics critical to loop performance are loop shape, loop size, inductance, resistance, tuned frequency, feeder length and the location of the loop. This document considers these aspects however the reader should also consult the following Engineering application notes for a broader interpretation of this complex process.

ENGNOTE_Error_Analysis
ENGNOTE_Loop_Field_Analysis
ENGNOTE_Q_Description
ENGNOTE_Xtalk
ENGNOTE_Loop_feeder_length
The document "Loop Format Analysis.pdf" – original study by Morris, Dean and Hulscher while dated (1980) and focussed on Traffic Intersection loops provides an informed perspective on loop shape/configuration.

Summary information relevant to these specific topics is detailed in this document – a more detailed description and analysis is found in each document.

Electrical Characteristics

The typical motorway loop used for incident detection and vehicle classification is a 2mt square loop with 4 turns. The ENGNOTE FIELD ANALYSIS document describes the performance of a square loop and a rectangular loop in relation to the field created and its inherent ability to interact with 'eddystone' fields located in the metal vehicle.

Loop Length	Loop Width	Number of turns	Resistance	Inductance
2mts	2mts	3	0.1 – 0.25	330uhenries
2mts	2mts	4	0.2 – 0.25	380uhenries

It is desirable for optimum classification performance to install a loop (combined with feeder) to have a measured 'Q' between 15 and 30. The inductance may vary according to the road base, temperature and climatic conditions (water on the road).

NOTE Investigation has revealed that 'Quadripole loop formats' are unsuitable for motorway detection due to their 'tight parallel electromagnetic field" which may induce detection dropout when a high-bed vehicle passes over the loop ie., counted as 2 or 3 vehicles. :

Loop properties must be within the following ranges:

- 50µH – 700µH loop inductance, (100 - 200µH recommended, depending on feeder length.)
- Q between 10 and 30 @ 40kHz, (20 recommended.)

Refer to Addendum A - Determining Loop Inductance for further information concerning the calculation of inductance.

Loop 'Q'

The Q of the loop determines the loop's performance:

$$Q = \frac{2\pi \times \text{frequency (Hz)} \times \text{inductance (H)}}{\text{resistance } (\Omega)}$$

Loops with lower Q will be less sensitive, and therefore won't detect a vehicle as quickly. While this will not adversely affect speed measurements, it will affect the length measurements of smaller cars. Loops with long feeder cable lengths may have a higher resistance and therefore lower Q. To compensate these loops should be given a higher inductance (more turns). For existing sites with low Q loops, using the most sensitive detector setting and adjusting the loop length in software will give more accurate measurements. See Section: Error Analysis for more information on adjusting for low Q loops. **Refer to** ENGNOTE_Q_Description for further information.

Feeder Length

For every meter of feeder, you would increase the "feeder" Inductance (Microhenries) by 0.62, therefore, for a feeder length of 500m the inductance in the feeder will be approximately 300 microhenries (a little over) . Feeder resistance is a significant contributor to reducing 'Q' which determines the performance of the loop. Feeder resistance increase by about .7ohms per 50 metres of installed feeder cable. Refer to the following table for information concerning these cable attributes.

The detection performance implications for feeder inductance in this example means that the loop itself has to exceed 300 Microhenries otherwise the feeder induction will cancel out the loop induction. A final loop inductance (after the feeder 'loss' is taken into consideration) should be approximately 180 to 320 microhenries. This varies according to the number of turns, size of loop and to some extent the road sub-base. The Engineering note related to loops provides a more in-depth analysis of the relationship between loops and inductance.

Length of Feeder	**Increase Resistance**	**Increase inductance**	**Decrease 'Q'**
50Mts	0.7ohms	33uhenries	-3
100Mts	1.4ohms	67uhenries	-5
150Mts	2.0ohms	100uhenries	-7
200mts	2.7ohms	133uhenries	-9

"Q" decrease primarily as a consequence of resistance

Refer to ENGNOTE_Loop_feeder_length for further information.

Depth of Loop

Vehicle detection utilizing loops is based on electromagnetic field interaction and the fundamental rule in electromagnetic field 'force' or degree of interaction is the $1/d^2$ relationship whereby a change in distance has an exponential effect on strength of the field.

Field analysis indicates that in order to detect trucks with loops buried at say 450mm and the main axels of the trucks sitting higher than regular cars, it has been observed that a loop with an output of at least 500 Microhenries is required.

While the calculations indicate this can be achieved within the given size of the roadway by installing; 3M wide by 20m long and 5 turns of wire in the loop head. This is not feasible as the loop size is governed by lane width in motorway applications.
The standard 4 turn two metre square Australian Motorway incident detection loop is approximately 230 Microhenries (will vary with road base). Removing or adding windings produces a fixed multiple change, therefore additional turns will compensate for the depth. It is desirable however that the maximum depth be 20cms.
Refer to ENGNOTE_LOOP_FIELD ANALYSIS for further information.

Cross Talk

When in-pavement loops operate at very similar frequencies a vehicle actuation can be ‘coupled’ to another detector input (ghost vehicle or false trigger results). This will only occur when the loop frequencies are the same (or very similar) and the two loops are active at the same time **and** the unshielded wires are in close proximity ie., same road slot. This can not occur when a single 8 channel scanning detector card is used as two loops will not be excited simultaneously as each channel is excited in sequence from 1-8. However when more than one card is used, the probability of a loop from each card being excited simultaneously increases as two or more cards are exciting loops in a cyclic rate around 250-300microseconds per channel. Good design practices ensures that the unshielded loop tails are not in close proximity however if loop tails are in close proximity then there is a likelihood that energy will be coupled and Xtalk will occur.

There are a number of postulations on eliminating XTalk including varying a fixed capacitance value, software control eliminating simultaneous excitation however the most appropriate method is site design. Best work practice site design eliminates Xtalk problems by ensuring feeder wires are not located in the same slot inadvertently or otherwise during installation.
Refer to ENGNOTE_XTalk for further information on the effectiveness of these actions in eliminating XTalk between loops.

Loop Configurations / Connection

Paired Loops

To measure vehicle and traffic values, two loops are required for each lane. The loops must be the same size and positioned a set distance apart longitudinally in the lane.

If one loop in the loop pair for a lane stops functioning, the vehicle will still be counted however speed and length will be 0. If both loops stop functioning, no vehicles can be counted.

Speed

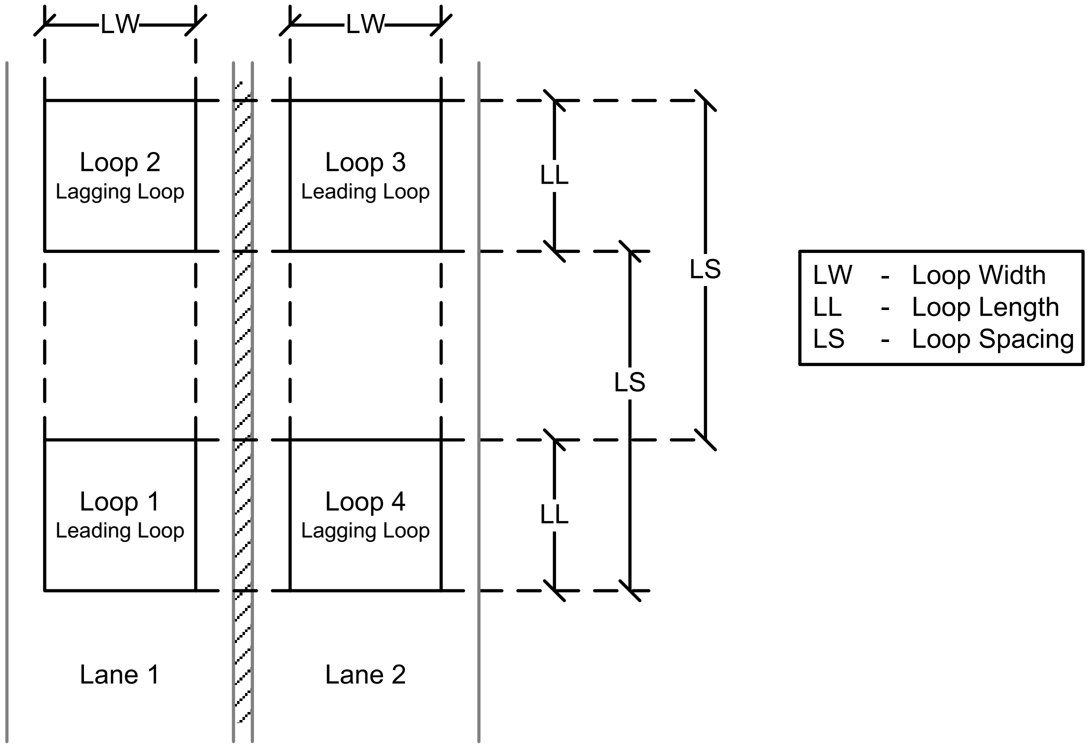
Vehicle speed is calculated using the spacing of the loops in the loop pair and the time between leading loop and lagging loop actuation for a vehicle travelling in the lane:

$$\boxed{\text{Speed} = \frac{\text{Loop Spacing}}{\text{Time between loops}}}$$

Two speed measurements are calculated. The first uses the time between actuation of the leading loop and actuation of the lagging loop and the second uses the time between clearing of the loops. The reported vehicle speed is an average of the two measurements.

Accuracy: ± 1.5 km/h @ 5m loop spacing.
Precision: 1 km/h

Therefore the measurement entered into the detector indicating spacing between the loop pair is critical to the accuracy of the speed measurement



Number of Lanes

The LVD supports up to 16 lanes. The number of lanes must be set before use, as it determines which lanes are active and which lanes record data.

Loop Connection

Loops must be connected to the detector in sequential pairs. The first loop in the pair must connect to loop input 1, 3, 5 or 7, and the second loop in the pair must connect to the immediate next loop – 2, 4, 6 or 8 respectively. This is the *forward* direction.

Lanes can be connected in *reverse*, i.e. lagging loop then leading loop. However this is not recommended. For reversible lanes the lane direction can be specified in software as forward or reverse.

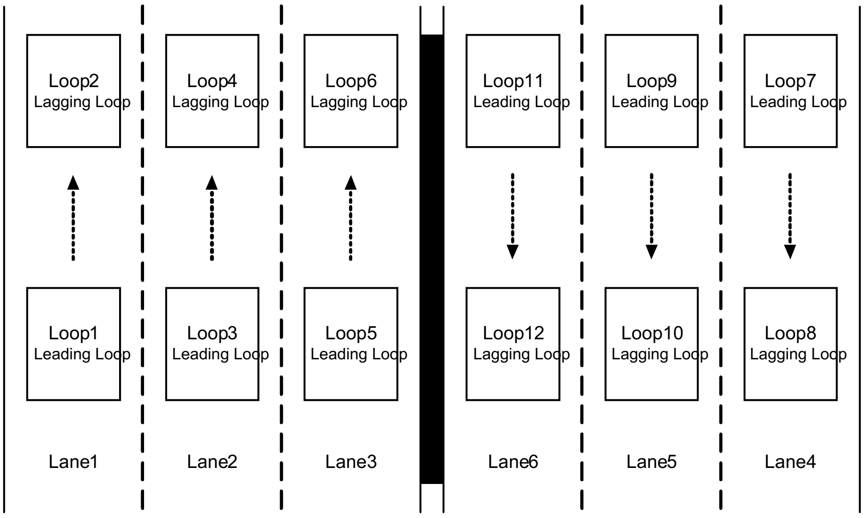
Site Orientation

For multiple installations, detector sites should be consistently configured such that lane 1 is always on the same side of the road. This makes interpreting results much easier.

Example 6 Lane Configuration

The diagram below shows the preferred layout of loops for a 6 lane system. The arrows indicate the direction of travel of vehicles in the lanes (left hand drive).

Note: While 'cross-talk' minimisation software is incorporated in the loop detector, loop feeders for loops that are connected to different detector cards as a general practice should NOT return to the cabinet in the same slot.



Addendum A - Determining Loop Inductance

Simple Formulae for calculating Inductance

Calculating Inductance

$$\frac{(l+w) \times (n^2+n)}{2} = \mu H \text{ (Micro-henries)}$$

l = Length traveled through or Length along lane, in feet (ft)
w = Loop Width Across lane, in feet (ft)
n = Number of Turns

Eg. l= 1800mm=5.905494ft
w= 1200mm=3.96996
n= 4

$$\frac{(6+4) \times (4^2+4)}{2} = 100\mu H$$

A more complex perspective for calculating Inductance

CALCULATING INDUCTANCE

Several simplified formulas are available for calculating the approximate inductance of an inductive-loop detector.

The simplified formulas provide acceptable accuracy for the self inductance of multiturn, rectangular, quadrupole, and circular loops, which have a large area relative to the conductor spacing. The approximations compare favorably with a range of measured inductive-loop inductance values.

The following table has been reprinted from the Traffic Detector Handbook: 3rd Edition Volume 1 Publication Number:FHWA-HRT-06-108 May 2006. Inductance and quality factor for several numbers of turns of wire were calculated using the mutual coupling formula discussed later in this chapter.

Table 2-7. Influence of lead-in cable type and length on *Q*.

Turns of #14 AWG wire in loop	Lead-in cable type, Belden	Lead-in cable length (ft)	Cable wire gauge (AWG)	Total parallel capac. (µF)	Series loop induct. (µH)	Lead-in cable induct† (µH)	Total series induct. (µH)	Loop resist.* (Ω)	Lead-in cable resist.†,** (Ω)	Total series resist. (Ω)	Loop system *Q*	Loop system loaded *Q* (kΩ)
3	8718	100	12	0.674	74	20	94	0.25	0.62	0.87	14	12
3	8720	100	14	0.670	74	21	95	0.25	0.80	1.05	11	10
3	8719	100	16	0.670	74	21	95	0.25	1.00	1.25	10	9
4	8718	100	12	0.437	125	20	145	0.33	0.62	0.95	19	14
4	8720	100	14	0.434	125	21	146	0.33	0.80	1.13	16	13
4	8719	100	16	0.434	125	21	146	0.33	1.00	1.33	14	11
5	8718	100	12	0.312	186	20	206	0.42	0.62	1.04	25	15
5	8720	100	14	0.306	186	21	207	0.42	0.80	1.22	21	14
5	8719	100	16	0.306	186	21	207	0.42	1.00	1.42	18	12
5	8718	1,000	12	0.172	186	200	386	0.42	6.20	6.62	7	5
5	8720	1,000	14	0.160	186	210	396	0.42	8.00	8.42	6	5
5	8719	1,000	16	0.160	186	210	396	0.42	10.00	10.42	5	4

Loop size is 6 x 6 ft (1.8 x 1.8 m). Excitation frequency is 20 kHz.
* Measured series resistance of loop 3 ft (0.9 m) above the laboratory floor.
** 8719 resistance value estimated.
† Lead-in cable length is 100 ft.

LOOP SYSTEM INDUCTANCE CALCULATIONS

Inductance attributed to the lead-in cable is added to wire loop inductance at the rate of 21 µH per 100 ft (30 m) of #14 AWG lead-in cable. For example, a 6- x 6-ft (1.8- x 1.8-m) rectangular loop should have three turns, according to Appendix C, and an inductance of 74 µH. If the lead-in cable is 200 feet (61 m) in length, the total inductance is

(2-14)

The inductance *L* of two or more loops connected in series is additive such that $L = L_1 + L_2 \pm 2M$, where L_1 and L_2 represent the inductance of each of the individual series-connected loops, *M* is the mutual inductance between the two loops, and the sign of *M* is positive if flux is increased by current flowing in the same direction in the closest spaced loop wires.

The mutual inductance is negligible when the loops are separated by a large distance. In this case, $L = L_1 + L_2$, i.e., the loops are connected in series producing maximum loop inductance.

If the loops are connected in parallel, then the combined inductance is calculated as $1/L = 1/L_1 + 1/L_2$. For example, the combined inductance of two 6- x 6-ft (1.8- x 1.8-m) loops of three turns each connected in parallel is given by

$$\frac{1}{L} = \frac{1}{74} + \frac{1}{74} = \frac{2}{74}$$

(2-15)

Thus, $2L = 74$ µH and $L = 37$ µH.

Thus, parallel connection of loops reduces the inductance. Good design practice requires that the combined loop inductance be greater than the lower limit of 50 µH. Therefore, the parallel connection described above is not suitable as a vehicle sensor.

In some cases, both series and parallel connections of inductive loops are desirable. Consider, for example, four 6- x 6-ft (1.8- x 1.8-m) three-turn loops installed 9 ft (2.7 m) apart to provide detection in a left-turn lane. Three possible types of connections are shown in Figure 2-8. Connection in series produces an inductance of 4 x 74 = 296 µH. Parallel connection produces only 18.5 µH ($4L = 74$ µH, $L = 18.5$ µH). A series-parallel configuration, where the upper two loops are connected in series and the bottom two loops are connected in series, produces two loop pairs, which are then connected in parallel to give a combined inductance of 74 µH.

Loop Inductance – Schedule of Calculated versus Measured

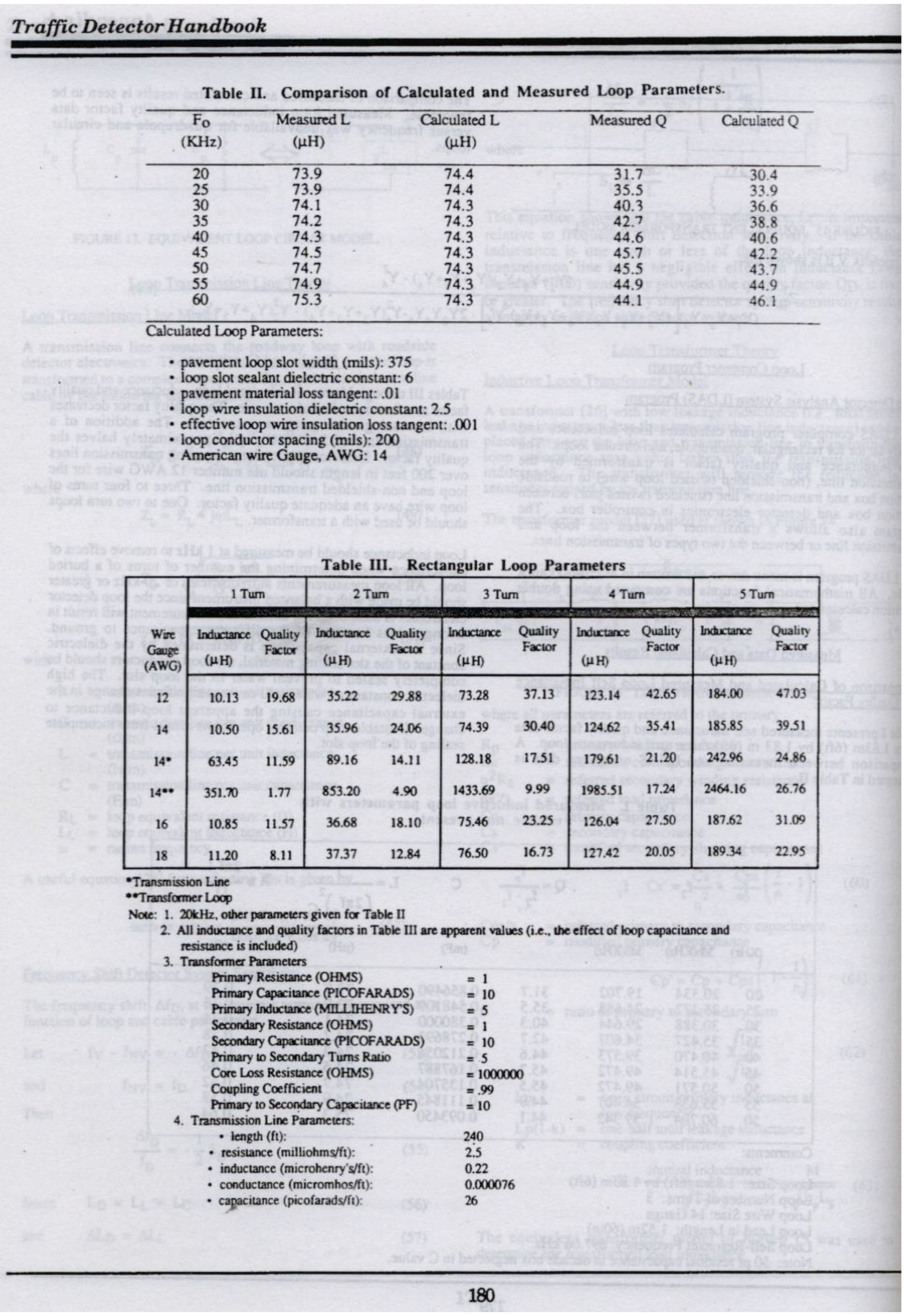


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Table II. Comparison of Calculated and Measured Loop Parameters.

F_0 (KHz)	Measured L (µH)	Calculated L (µH)	Measured Q	Calculated Q
20	73.9	74.4	31.7	30.4
25	73.9	74.4	35.5	33.9
30	74.1	74.3	40.3	36.6
35	74.2	74.3	42.7	38.8
40	74.3	74.3	44.6	40.6
45	74.5	74.3	45.7	42.2
50	74.7	74.3	45.5	43.7
55	74.9	74.3	44.9	44.9
60	75.3	74.3	44.1	46.1

Calculated Loop Parameters:

- pavement loop slot width (mils): 375
- loop slot sealant dielectric constant: 6
- pavement material loss tangent: .01
- loop wire insulation dielectric constant: 2.5
- effective loop wire insulation loss tangent: .001
- loop conductor spacing (mils): 200
- American wire Gauge, AWG: 14

Table III. Rectangular Loop Parameters

	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
Wire Gauge (AWG)	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor
12	10.13	19.68	35.22	29.88	73.28	37.13	123.14	42.65	184.00	47.03
14	10.50	15.61	35.96	24.06	74.39	30.40	124.62	35.41	185.85	39.51
14*	63.45	11.59	89.16	14.11	128.18	17.51	179.61	21.20	242.96	24.86
14**	351.70	1.77	853.20	4.90	1433.69	9.99	1985.51	17.24	2464.16	26.76
16	10.85	11.57	36.68	18.10	75.46	23.25	126.04	27.50	187.62	31.09
18	11.20	8.11	37.37	12.84	76.50	16.73	127.42	20.05	189.34	22.95

*Transmission Line

**Transformer Loop

Note: 1. 20kHz, other parameters given for Table II

2. All inductance and quality factors in Table III are apparent values (i.e., the effect of loop capacitance and resistance is included)

3. Transformer Parameters

Primary Resistance (OHMS) = 1
Primary Capacitance (PICOFARADS) = 10
Primary Inductance (MILLIHENRY'S) = 5
Secondary Resistance (OHMS) = 1
Secondary Capacitance (PICOFARADS) = 10
Primary to Secondary Turns Ratio = 5
Core Loss Resistance (OHMS) = 1000000
Coupling Coefficient = .99
Primary to Secondary Capacitance (PF) = 10

4. Transmission Line Parameters:

• length (ft):	240
• resistance (milliohms/ft):	2.5
• inductance (microhenry's/ft):	0.22
• conductance (micromhos/ft):	0.000076
• capacitance (picofarads/ft):	26

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